NASA/TM—97-206533

AIAA-98-0177

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Prepared for the
36th Aerospace Sciences Meeting & Exhibit
sponsored by the American Institute of Aeronautics and Astronautics
Reno, Nevada, January 12–15, 1998

National Aeronautics and
Space Administration

Lewis Research Center

December 1997

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FAN NOISE PREDICTION: STATUS AND NEEDS

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Abstract

The prediction of fan noise is an important part to the prediction of overall turbofan engine noise. Advances in computers and better understanding of the flow physics have allowed researchers to compute sound generation from first principles and rely less on empirical correlations. While progress has been made, there are still many aspects of the problem that need to be explored. This paper presents some recent advances in fan noise prediction and suggests areas that still need further development. Fan noise predictions that support the recommendations are taken from existing publications.

Introduction

This paper is not meant to be a thorough review of all work related to fan noise prediction. It contains recommendations for future research in fan noise for subsonic aircraft engines based on the current status of fan noise prediction, mostly within NASA's research programs.

Dominant noise sources for turbofan engines are identified in Fig. 1 (Ref. 1). As the bypass ratio of engines increase beyond ten, jet noise is being reduced to the point where fan noise becomes the primary noise source (Ref. 2). It is generally accepted that fan noise is produced by the following sources:

1. Inlet boundary layer or inflow distortions interacting with the fan
2. Self noise from the fan
3. Fan wakes interacting with stators or struts

There are a variety of predictions methods being developed that either try to model all of these sources simultaneously, or consider them as components. Key aspects to either approach include accurate prediction of the steady and unsteady flow field through the fan stage, analysis of the fluctuating pressures on the aerodynamic surfaces, the generation of sound from the fluctuating pressures, and the propagation/radiation of the sound to the far field.

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The ultimate goal for fan noise prediction is to be able to accurately predict the absolute levels for sound as it propagates away from the engine. This includes properly modeling the effects of changes to geometric features and flow conditions. An alternate goal is to be able to predict the correct trends of sound as a function of geometry and flow field changes. Neither of these objectives have been fully achieved, although there has been considerable progress.

This paper is divided into two categories: tone noise and broadband noise. In each category, noise resulting from both interaction and self noise sources are discussed. Finally, the status of Computational AeroAcoustics (CAA) for fan noise prediction is presented.

Tone Noise

Fan tone noise is generated by either rotor-alone or rotor/stator/strut interaction with flow distortions. Fan wakes interacting with stators is one of the principle noise sources for fans with subsonic tip speeds. As a result, there has been a lot of work done to predict the unsteady aerodynamics associated with gusts (prescribed fan wakes) interacting with airfoils. Most of this work has been done for two-dimensional flows, but this has changed in recent years with better computing technology and a greater understanding of the three-dimensional flow physics.

Interaction Noise

A common approach for predicting interaction tone noise is to use modal analysis in conjunction with the Tyler-Sofrin theory (Ref. 3). Fan wakes or inlet distortions are specified as vortical gusts based on empirical correlations from model or full scale engine tests. The gusts interact with the rotor or stator, generally represented as strips of airfoils or flat plates in a cascade. A "source" model is used to determine the unsteady surface pressures on the blades responding to the interaction with the vortical gusts. The sound generated in the nacelle is determined by coupling the unsteady surface pressures to the propagating duct modes for both the inlet and exhaust. A fan noise prediction code originally developed in the early 1980's (Ref. 4), and revised in the 1990's (Ref. 5), uses this approach. Radiation codes have been developed (Refs. 24 to 29) to predict the propagation of these modes to the far field. This procedure is repeated for each frequency where interaction tones exist, i.e., the Blade Passing Frequency (BPF) and higher harmonics. Figure 2 shows a schematic of the process.

Source Models. Many of the current source models use a "strip" approximation for the unsteady aerodynamics. The blades are represented as two-dimensional, flat plate cascades stacked in the spanwise direction. These models were developed in the early 1970's by Smith (Ref. 6), Whitehead (Ref. 7) and Kaji (Ref. 8). A disturbance corresponding to either an inflow distortion into the fan or the fan wake interacting with the stators/struts are prescribed as vortical gusts that convect with the mean flow (the "frozen gust" assumption). The unsteady surface pressures on the blades are determined by satisfying a no flow boundary condition normal to the plate and can be represented as a distribution of dipoles in the chordwise direction. Applications and extensions of these models have led to the understanding that chordwise source non-compactness effects are important for tone predictions (Refs. 9 to 12). The unsteady surface pressures are integrated and coupled to the propagating duct modes inside the nacelle to determine the inlet and exhaust sound power levels.

Using strip theory for the source model always raises questions of validity. Namba (Ref. 10), who developed a three-dimensional lifting surface analysis, reported that the three-dimensional effects become less important for a given spanwise gust wave number as the acoustic response frequency increases. This was also verified by Kobayashi (Ref. 11) who assessed the importance of including three-dimensional effects by comparing strip theory to a three-dimensional lifting surface code for several fans. He concludes that "two-dimensional calculations of the unsteady forces are reasonably adequate for fan noise prediction." The acoustic power of the duct modes agreed to within ±2 dB. At this time, most of the applications were concerned with inflow distortions from either inlet guide vanes, inlet boundary layers, or engine angle-of-attack. Today, inlet guide vanes are less common in turbofan engines and inlet design technology has evolved to where inflow distortions are not as severe. The emphasis has now changed to fan wakes interacting with stators and struts. It should also be pointed out that all of this work was done for subsonic flows. While this may be adequate for fan/stator interaction where the mean flow is subsonic, disturbances interacting with the rotor typically involve supersonic relative flows near the tip of the fan. Even transonic flow can significantly distort the vortical gusts and change the local propagation characteristics of the acoustic energy (Ref. 15).

Concerns about "real" blade effects for both aeroacoustic and aeroelastic applications have led unsteady aerodynamicists to develop computational methods for the gust response problem. Frequency domain approaches typically use perturbation methods from a nonlinear, two-dimensional mean flow (Refs. 13 to 16). There have been a few applications of these class of codes to aeroacoustic problems. Preliminary results indicate that gusts convecting through a cascade of airfoils with a transonic mean flow can generate significantly different sound. Figure 3 was taken from Atassi, Fang and Hardy (Ref. 15) and shows how the upstream and downstream acoustic pressure can be significantly different for an airfoil in transonic flow when compared to a flat plate calculation. They conclude that the magnitude of the acoustic modes can be significantly larger for a loaded cascade. Lorence and Hall (Ref. 16) applied a similar analysis to study the sensitivity of sound to design variables like blade thickness, camber, and stagger angle. They found that it is possible to redistribute the inlet and aft sound levels by varying these parameters, but the overall levels were not significantly changed.

Three-dimensional versions of these methods are now being developed. An analysis based on the linearized Euler equations has been developed by Montgomery and Verdon (Ref. 17) for turbomachinery applications. The unsteady flow field is assumed to be a small perturbation from the nonlinear steady flow. This method uses modal analysis and the solutions are determined for a single blade passage, which helps reduce computational requirements. Since this approach analyzes the fan and stator as separate components, the unsteady boundary conditions in the interstage region where swirling flow exists have presented a major computational technology hurdle (Refs. 18 and 19). One way to circumvent this difficulty is to model both the fan and the stator simultaneously, which eliminates the computational boundary in the swirl region. This has been done by Rangwalla and Rai (Ref. 20) for acoustic applications. This approach relies on the analysis to predict the fan wake properties (as opposed to specifying the wake from data or other analyses) and requires solutions from multiple blade passages to account for uneven fan/stator blade counts. Since the grid representing the fan blades rotates relative to the stator grid, sufficiently small time steps are needed to accurately transmit the acoustic waves across the interface boundary (Ref. 21). All of these issues make time-marching solutions for interaction tone predictions difficult, requiring hundreds of hours of CPU time to obtain accurate three-dimensional solutions for even one fan speed/configuration.

Very little has been done yet to apply the three-dimensional codes to aeroacoustic fan problems. Parametric studies are needed to determine when the two-dimensional flat plate models can be used and when more complex codes are needed, particularly for transonic flows. It is unlikely that the three-dimensional codes that solve the Euler or Navier-Stokes equations will be used in a design environment in the near future, but they can be used to sort out what is important for improving fan noise prediction methods.

An outstanding issue for any of the approaches mentioned so far is how to deal with near sonic flows on the fan. All discretized approaches have problems when the local Mach number is nearly one and the acoustic wavelengths become small for upstream propagating waves. Many of the current computational methods require 10 to 20 points/wavelength to accurately model the acoustics. Can these regions near the blade be ignored? Studies are needed that identify how severe this problem is for fan applications.

When the source model is used for a single blade row, specification of the fan wake is usually done through empirical correlations. Important parameters for tone predictions include wake width and depth as a function of axial distance between the fan and stators. Wake models based on measured data have been developed (Ref. 22) and updated as more fans are tested. The correlations relate the wakes to local characteristics of the fan, like blade section drag and loading. A disadvantage of this approach is that correlations may not be representative of a particular fan. Sutliff, et al. (Ref. 23) compared acoustic predictions using measured fan wakes versus empirical wake correlations. They found that the differences between measured and correlated wake characteristics can influence the duct power by a few decibels (Fig. 4), but the trends are similar as a function of fan speed (for a subsonic rotor). Ultimately, CFD predictions may be used to provide wake properties for a specific fan design. Since the acoustic source models need this information near the stators, CFD codes need to be able to accurately convect the wakes over a few fan chord lengths.

Duct Propagation and Radiation Models. There are a variety of approaches available for propagating the sound through the nacelle and predicting far field levels. Input is required that specifies source levels from either predictions or experimental measurements. Early methods based on ray tracing and Wiener-Hopf methods (Ref. 24) were developed that are quick, but typically do not include flow effects with realistic geometry. There were also methods available that analyze the modal characteristics of the source (based on cut-off ratio) to project far field directivity and sound levels (Ref. 25). These methods include convection effects assuming a uniform mean flow through the duct. Numerical methods have been developed that account for mean flow variations and acoustic wave interactions with curved center bodies and ducts. This was initially done for inlet radiation problems (Refs. 26 to 28), and later extended to the nozzle radiation problem (Ref. 29). An important aspect for aft radiation is including the refraction effects from the nozzle shear layer. These methods use a two-dimensional grid that cuts the engine in an x-r plane (Fig. 2) and uses duct mode information as input at a specific axial plane inside the nacelle. Applications of the numerical methods are usually restricted to frequencies around 3 BPF and below for a typical fan. This is constrained by grid size requirements and practical CPU times on current computers.

Results from predictions have been encouraging for axisymmetric nacelles. Improvements in measurement techniques (Ref. 30) that determine duct mode source strengths have allowed researchers to validate propagation codes. Heidelberg, et al. (Ref. 31) have shown how these codes can do an excellent job of predicting far field directivity when the source levels are known (Fig. 5). Improvements have been made (Ref. 32) in the midangle regions by properly accounting for the inlet and aft mode phase relationships. These results suggest that work should concentrate on source models that can accurately predict the duct modes in the nacelle.

The radiation code cited in Refs. 28 and 29, uses finite element analysis in the near field and a wave envelope method to obtain far field information. This method gives good overall results for sound pressure amplitudes, but falls short if both amplitude and phase information are needed. Spence (Ref. 33) recently showed how phase accuracy can be improved by using a Kirchhoff analysis in place of the wave envelope method.

The methods presented above assume axisymmetric nacelle geometries. In reality, turbofan engines have asymmetric nacelles, struts and pylons, requiring three-dimensional analyses. Advances in computing technology and development of highly efficient methods offer ways to meet these needs (Refs. 34 and 35).

System Predictions. In recent years, the effects of mode trapping between the fan and stator due to swirling flows, transmission effects through the fan, frequency scattering and reflections from the inlet/nozzle have also been included in fan noise prediction (Refs. 36 to 40).

Again, the approach is to use components consisting of the inlet, fan, stator and nozzle. Influence coefficients are used at the interface boundaries to model interactions from all components. Topol (Ref. 39) recently presented sample predictions for a subsonic fan and compared them with experimental data from a model scale test (Fig. 6). The results show that including coupling and swirl effects can significantly change the predicted directivity of the interaction tones. Overall, it looks like the predictions are in better agreement with the data, but more applications are needed. Sijtsma, Rademaker, and Schulten (Ref. 41) also reported that reflections from the inlet and nozzle can be significant over a wide range of speeds and should be included in fan noise predictions. Schulten's method (Ref. 42) uses a three-dimensional lifting surface code for the source model.

System predictions that model multiple components of an engine have been needed for many years and are finally being developed. The next step is to determine when system predictions are needed over simpler approaches. System predictions are considerably more complex and require expert users, at least for now.

Multiple Pure Tones

Predictions for Multiple Pure Tone (MPT or "buzz-saw") noise are typically not robust. This noise source is caused by variations in the fan blade geometry (like stagger angle) that results from either manufacturing or installation. Unless careful inspection is done for each fan after production, it is difficult to know what the MPT characteristics will be in advance. The spectra for MPT noise is experimentally distinguished by observing shaft-order tones in the near field inlet microphone measurements as the fan speed becomes supersonic. Prediction methods need to input blade-to-blade variations in order to predict the orders of the shaft frequency where the tones will be a problem.

There has been work done recently to predict the fan speeds for the onset of MPT noise using CFD (Ref. 43). This approach only requires knowledge of the steady flow field near the fan since MPT noise can be related to the formation of shock waves. Sufficient grid resolution is needed to capture the bow shock from a single blade and its interaction with adjacent blades.

Broadband Noise

Methods for predicting fan broadband noise have been mostly empirical in nature. They usually rely on correlations from engine or model data that relate the measured fan broadband noise with fan loading and tip speed. Since the tone levels have been significantly reduced from modern turbofan engines with higher bypass ratios (Ref. 44), methods that can predict broadband noise with less empiricism are needed. Analyses that calculate the unsteady aerodynamics associated with broadband noise can use, in principle, the same gust response methods cited for tone noise prediction. However, many more frequency bands must be considered compared to tone prediction methods. This significantly increases the computational time. Time marching methods are also difficult to use since they need accurate resolution of the temporal and spatial flow properties. One of the underlying requirements for any pure prediction method for broadband noise is accurate representation of the flow turbulence. Another challenge to fan broadband noise is a general lack of understanding of important source mechanisms as the operating conditions vary. It is likely that the total broadband noise levels result from a number of different sources within the engine.

Interaction Noise

Broadband noise can result from either inflow turbulence interacting with the fan or fan turbulent wakes impinging on stators and struts. There is a version of the tone noise prediction code cited in Ref. 4 that also predicts broadband interaction noise. It uses a two-dimensional, flat plate gust response model for specific turbulence intensity levels and distributions. A sample prediction was done for a generic cascade subjected to vortical excitations that simulate the fan wake turbulence interacting with a stator. The turbulence was assumed to be isotropic at the stator leading edge with an intensity of 1 percent. The inlet sound power levels (taken from Ref. 4) are plotted in Fig. 7 for four different integral length scales and frequencies ranging from BPF to 3 BPF. As the integral length scale becomes sufficiently large, haystacking occurs near the harmonic frequencies. This work was one of the first attempts to predict fan broadband noise by first principle estimates of the source.

More recent work for interaction noise has been done by Mani, et al. (Ref. 45) and Martinez (Ref. 46). Mani uses a flat plate source model that includes both dipole and quadrupole distributions using a strip approach. The steady loading effects are estimated to assess quadrapole contributions. He shows how the quadrapole effects can be significant for higher frequencies when compared to the dipole contributions. Martinez has also investigated blade loading on fan broadband noise by applying a two-dimensional linearized Euler code (Ref. 47) to model "real" blade effects. This work is relatively new and has not yet been rigorously applied.

Fan-Alone Sources

Rotor blade self noise has been investigated for isolated airfoils by a number of researchers (see Refs. 48 and 49 for listings). Sources mechanisms for isolated airfoils include turbulent boundary layer/trailing edge noise, separation stall noise, laminar boundary layer vortex shedding noise, tip vortex formation noise, and trailing edge bluntness vortex shedding noise (Ref. 50). For ducted fan applications, these sources are influenced by the presence of the casing and hub. Glegg (Refs. 48 and 49) has extended this work to ducted fans by using measured spectra from the isolated airfoil tests to evaluate blade surface unsteady pressure distributions. The surface pressures were input to a strip approach for rotating blades (similar to methods described earlier in this paper) to determine mode amplitudes for a ducted fan. Results show that the duct sound power scales with the fifth power of the fan speed for low fan speeds, and the sixth power for high fan speeds. The effect of rotor incidence was determined through the experimental correlations for airfoil angle of attack. Glegg reports that blade incidence increases the self noise as 2.4 dB/degree for an unstalled fan. This is consistent with Gliebe (Ref. 51), who found that forward radiated fan broadband noise increases 2.5 dB/degree of incidence.

While this approach looks promising, it still relies on empirical relationships for the sound sources. Methods are needed that can accurately predict the source spectra, which ultimately depends on improved turbulence models.

Computational Aeroacoustics

Computational AeroAcoustics (CAA) has gained considerable attention over the past few years. If successful, it offers a way to reduce the number of component analyses needed to predict the total noise and provide a more realistic and accurate prediction tool. For example, fan tone and broadband noise can be computed together with the mean flow and unsteady pressures solved simultaneously. All nonlinearities and complexities associated with three-dimensional geometries in high-speed flows can be computed. An immediate challenge for CAA is to demonstrate accurate noise predictions in a reasonable amount of CPU time. For internal flows, unsteady boundary conditions are still an issue.

There have been various workshops and conference sessions dedicated to CAA and its applications to selected problems. The Second Computational Aeroacoustics Workshop on Benchmark Problems (Ref. 52) concentrated on applications to various model problems. One of the problems designed for turbomachinery noise applications uses the same two-dimensional gust response model utilized in the source model from Ref. 4 to benchmark state-of-the-art CAA codes. <u>It is imperative that CAA methods demonstrate accurate predictions of linear flows where analytical solutions can be used for comparisons, before attempting more difficult problems</u>. There is no reason to believe that a nonlinear code is producing accurate predictions if it cannot match a linear subset of the governing equations! The turbomachinery benchmark problem (designated "Category 3") calls for the solution to a gust convected with a mean flow interacting with an unstaggered cascade of flat plates (Fig. 8). Four passages are used with the gust phase offset by 90° for each plate (interblade phase angle). The amplitude of the gust is small so comparisons can be made with linear theory. Gust frequencies corresponding to reduced frequencies of about 8 and 20 (based on plate length) are prescribed and the inflow Mach number is 0.5. The resulting unsteady surface pressure distributions on the plate and the upstream/downstream sound intensity distributions are requested from each participant in the workshop.

Four predictions for this problem were submitted to the workshop and the results vary significantly. Comparisons for "Problem 2," which asks for solutions for a convected gust that is introduced upstream, are shown in Fig. 9 (low frequency case) and Fig. 10 (high frequency case). The pressure distributions show the first harmonic of the real and imaginary parts of the pressure differential distribution across the plate after a Fourier transform is applied to the unsteady pressures. The mean square pressure distributions (sound intensity) are shown along a line at $x = -2$ upstream of the cascade and along a line at $x = 3$ downstream of the cascade.

Reasons for discrepancies are likely to be due to either poor grid resolution, or problems with the unsteady boundary conditions at the inflow and outflow. It is possible that local nonlinearities may exist at the leading or trailing edges of the flat plate, but this can be assessed by simply reducing the gust amplitude. The CPU times for these runs vary from just a few minutes for the frequency domain solutions to many hours for the time marching solutions. Predictions for fan noise require extensions to three dimensional flows, including real blade effects for staggered cascades, running the entire rotor and stator blade passages instead of only the four used in this problem (time domain approaches), accurate prediction of the rotor wakes if including both the fan and stators, and accurate propagation of the acoustic waves to the far field (unless another code is used for duct propagation and radiation). For the time domain solvers, this makes the problem extremely complex and well beyond today's capabilities if the codes are to be used for design and analysis. However, progress in both the algorithm development for CAA codes and computer speeds make these efforts worth pursuing. For example, one of the solutions (Ref. 52, Lockard & Morris) was done using an algorithm for parallel computing and showed significant reductions in CPU time over traditional time-marching methods.

There have been other algorithms developed that have demonstrated potential for significant savings in CPU time. One approach (Ref. 34), called "Green's Function Discretation (GFD)" reduces the number of grid points per acoustic wavelength to numbers near the Nyquist criterion. This technique shows promise for being able to use CAA for three-dimensional applications.

Codes using advanced CAA algorithms need to be developed far enough to do noise predictions for fan designs where acoustic data is available. The best way to generate interest in CAA is to demonstrate that it can do a better job of predicting fan noise than current methods, even if this requires significantly more CPU time and user experience. The turbomachinery benchmark problem is a first step towards demonstrating what CAA algorithms can offer as an eventual substitute for simpler source models. Model problems for three-dimensional fan flows where analytical comparisons can be made do not yet exist. This is a problem that faces many applications of CAA and at some point, comparisons to experimental data will be the only available benchmark. However, there is a need for the community to define three-dimensional problems that researchers can use to compare the many prediction methods that are becoming available. Meetings, like the First and Second Computational Aeroacoustics Workshops, need to continue and lead the CAA community towards relevant applications that can eventually be used by industry.

Summary and Recommendations

Considerable progress has been made in recent years towards improving fan noise prediction. Portions of the work have been highlighted in this paper. Better knowledge and prediction of noise sources is a vital requirement for improving prediction methods. Duct propagation and radiation models do a good job of predicting far field levels if the source distribution/amplitude inside the nacelle can be accurately defined. As tone levels are being reduced in modern turbofan engines, emphasis is being shifted to the prediction of fan broadband noise. Efforts are needed to characterize turbulence spectra of the flow near the fan and stators, including intensity and integral length scale distributions. Research is needed that identifies the level of analysis required to accurately predict duct sound power levels.

The following recommendations are made regarding future work:

1. Apply three-dimensional source models to identify important flow physics from an acoustic perspective. Compare the results with two-dimensional source models for both tone and broadband noise predictions.
2. Apply source models that include "real" blade effects and compare them to flat plate source models for transonic flows. Study high Mach number flow effects on acoustic wave propagation through a fan.
3. Assess CFD capabilities to predict both steady and unsteady (turbulence spectra) for fan wakes near stator leading edges. Need to determine if descriptions of turbulence can be predicted, or should wake/boundary layer models be developed/updated from experimental measurements.
4. Continue development of highly efficient and accurate methods (through CAA or theory) that can solve three-dimensional problems like asymmetric nacelles. Work needs to continue in developing three-dimensional, unsteady boundary conditions for internal flows.
5. Run parametric studies for various engine configurations to identify when system predictions are needed (that include inlet, fan, stators, struts, and nozzles), as opposed to uncoupled methods that may neglect some components.
6. A study should be done to determine whether time-marching or frequency-domain methods are best suited for broadband noise predictions.
7. Need to define benchmark problems that address the three-dimensional aspects of fan noise prediction. The aeroacoustics community should work together to define these model problems. More code-to-code and code-to-data comparisons are needed to identify which sources should be included for providing accurate fan noise predictions.

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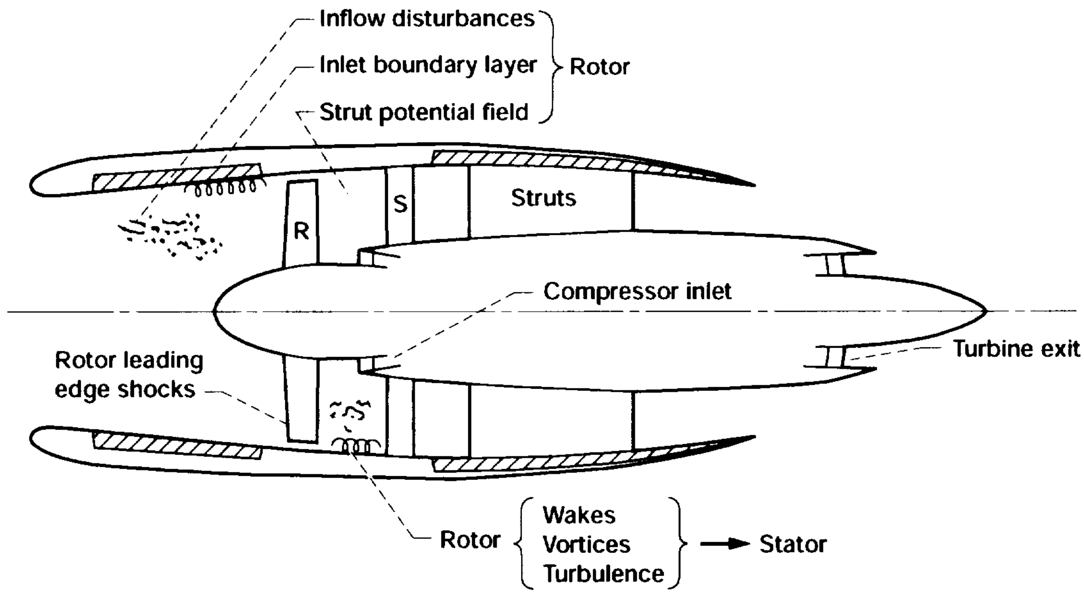

Figure 1.—Dominant noise sources for turbofan engines.

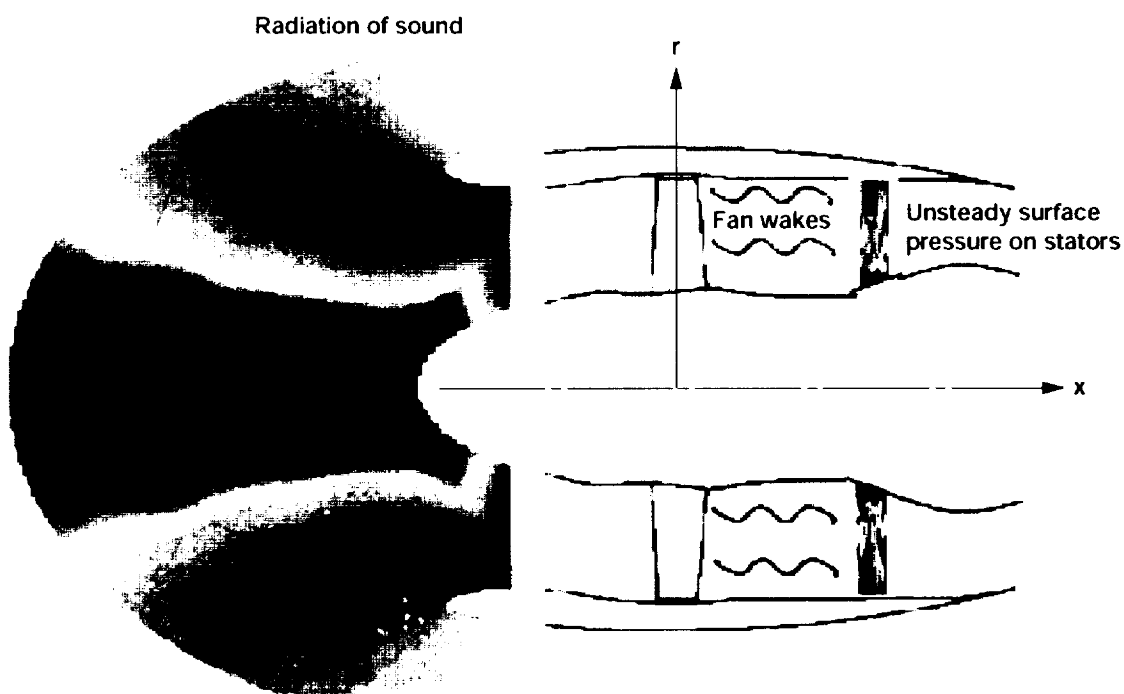

Figure 2.—Prediction of fan wake/stator interaction noise.

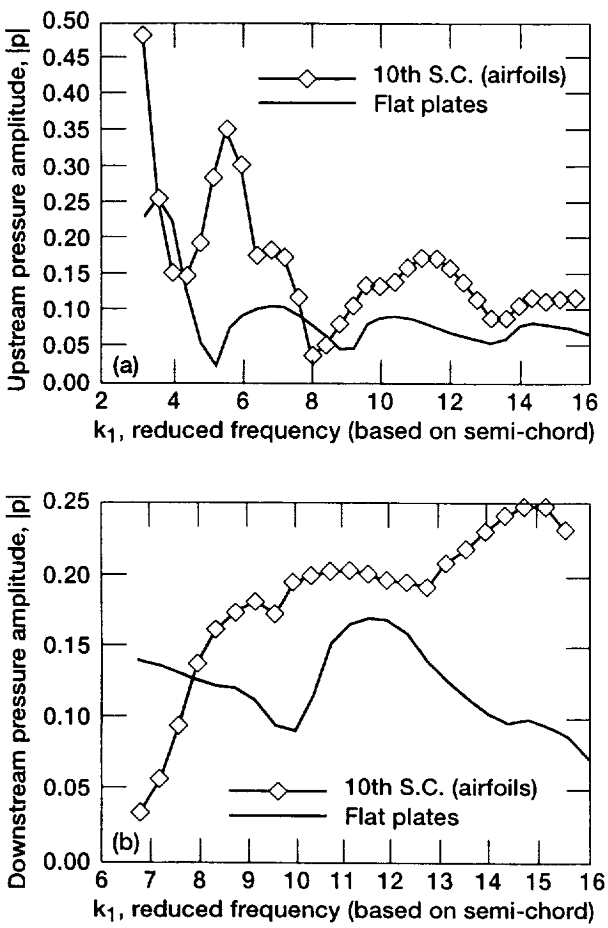

Figure 3.—Magnitude of downstream pressure for second acoustic mode, airfoil vs. flat plate response to gust, M_∞ = 0.8. (a) Upstream. (b) Downstream.

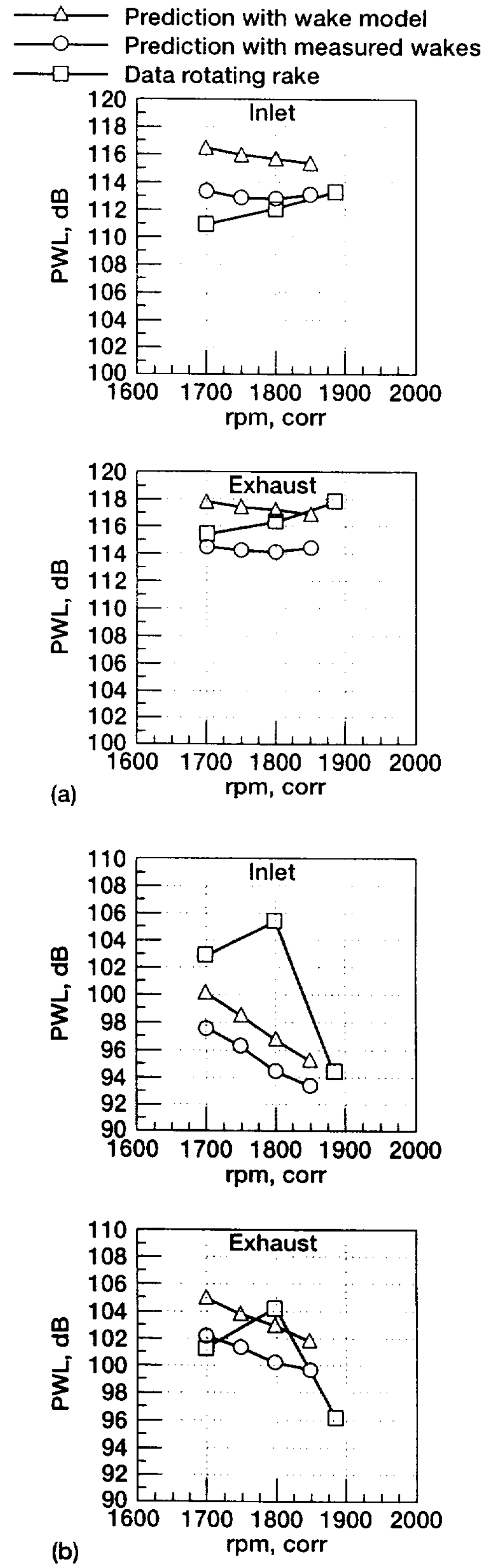

Figure 4.—Comparisons of duct mode power levels from NASA low-speed fan (48-in. diam). (a) BPF, 16 blades, 13 stator vanes, (3,0) mode. (b) 2 BPF, 16 blades, 13 stator vanes, sum of (6,0) and (–7,0) modes.

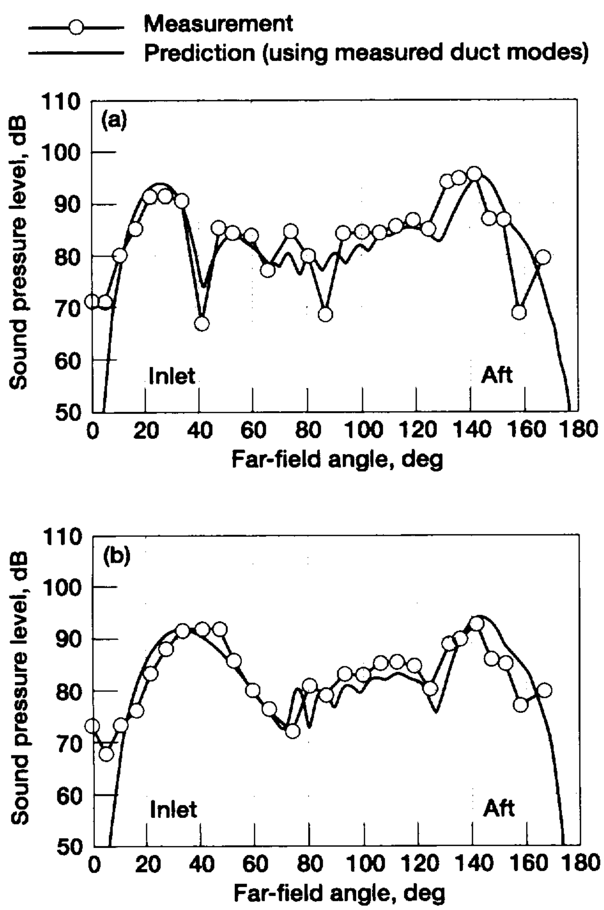

Figure 5.—Measured and predicted far-field directivity, 2 BPF, NASA low-speed fan (48-in. diam). (a) 1886 rpm. (b) 1700 rpm.

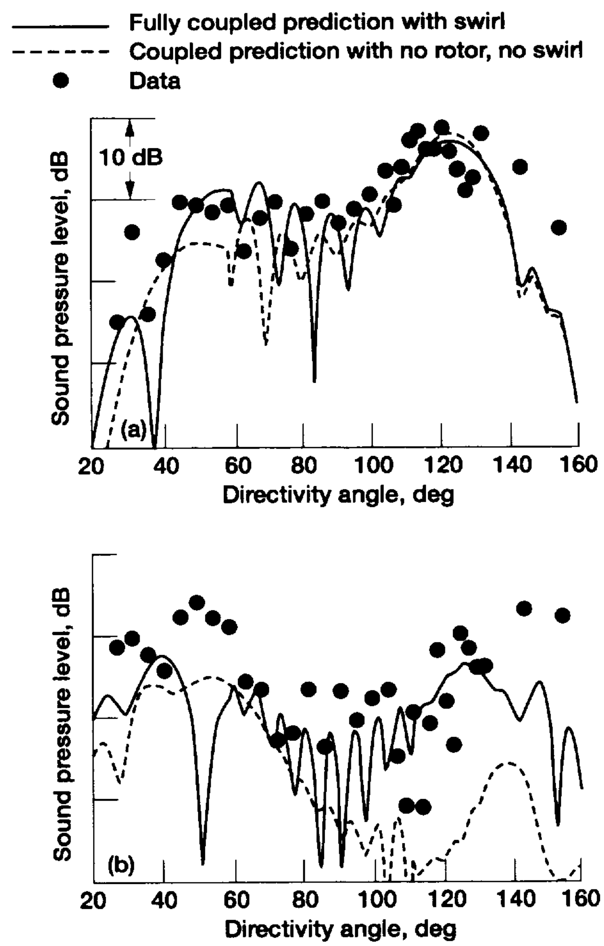

Figure 6.—System prediction of interaction tones for a subsonic fan. (a) 2 BPF. (b) 3 BPF.

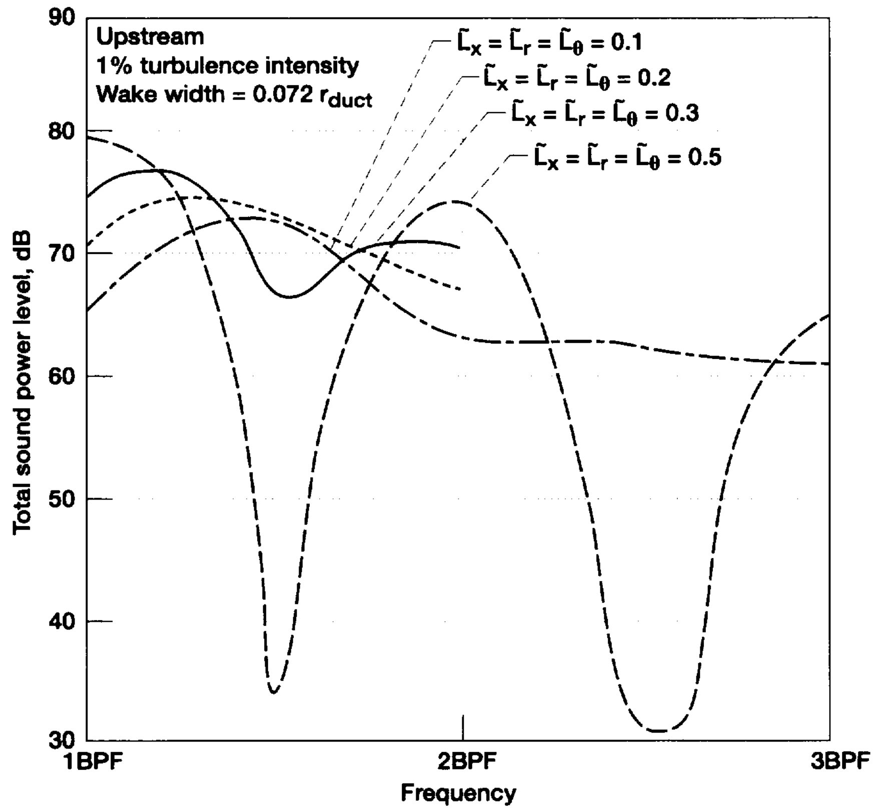

Figure 7.—Predictions of total duct sound power for various integral length scales of isotropic turbulence.

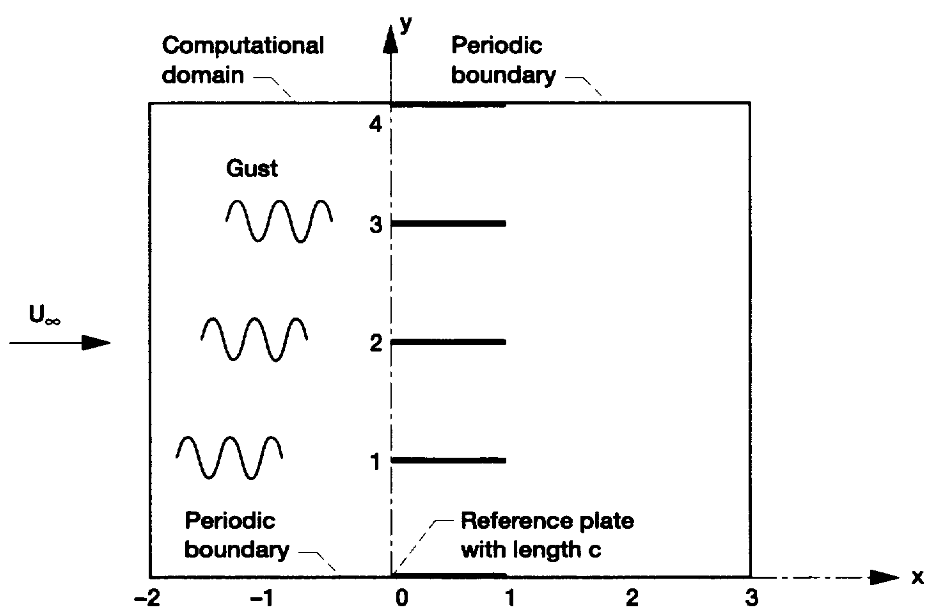

Figure 8.—Computational domain for turbomachinery noise benchmark problem, cascade of unstaggered flat plates interacting with a gust.

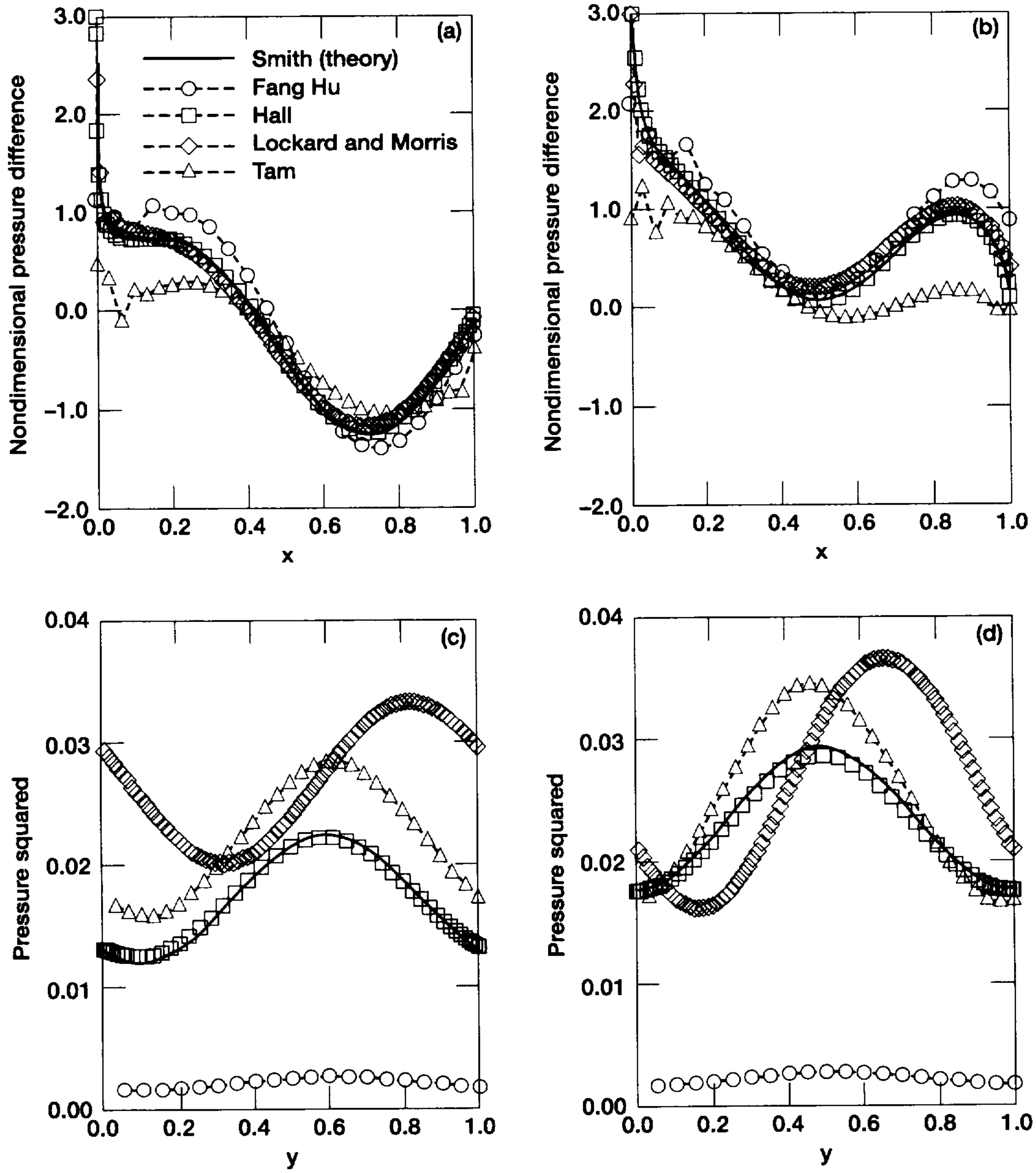

Figure 9.—Comparison of predictions for turbomachinery benchmark problem, low frequency case. (a) Unsteady pressure distribution, real. (b) Unsteady pressure distribution, imaginary. (c) Upstream mean square pressure, x = −2. (d) Downstream mean square pressure, x = 3.

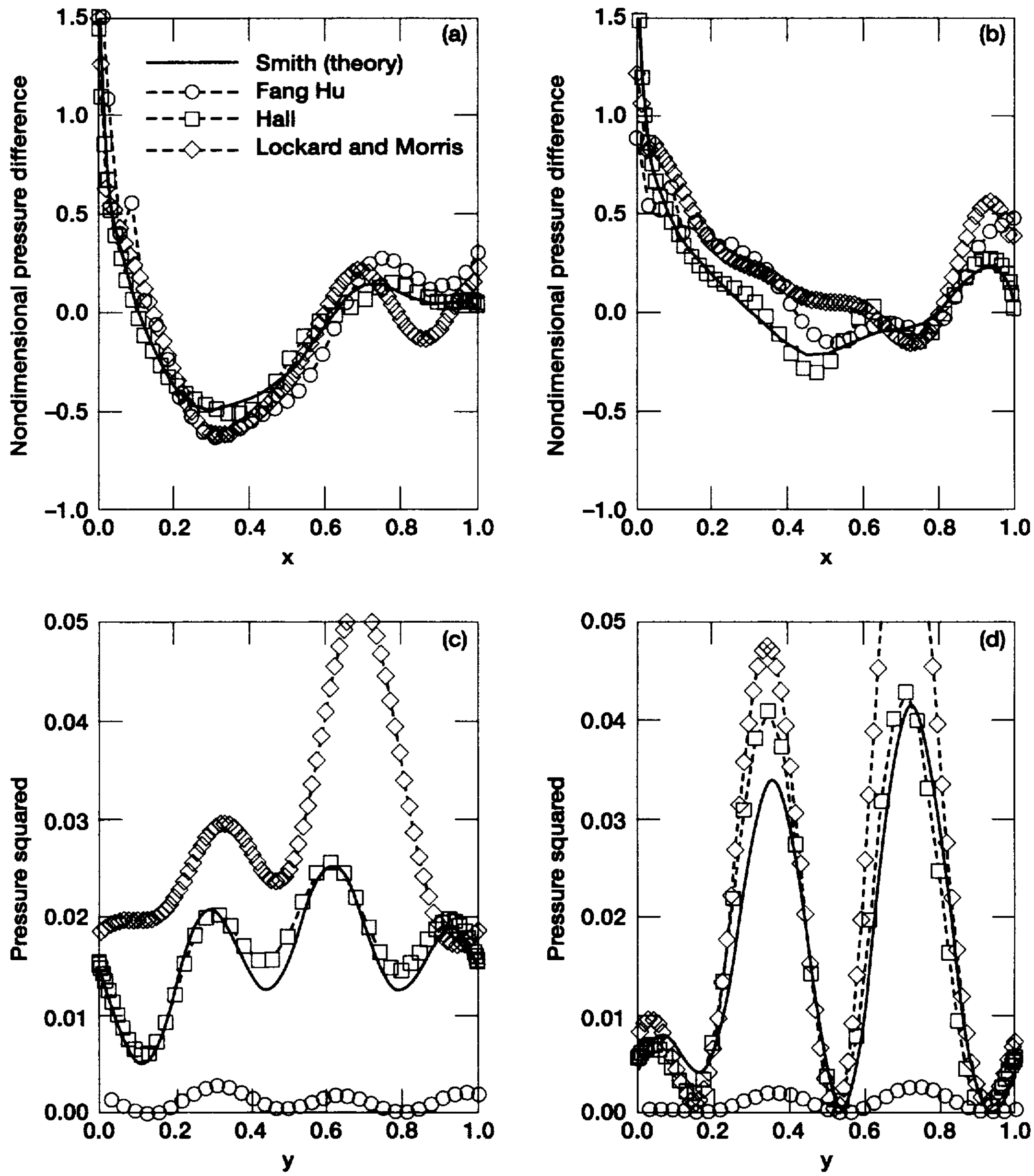

Figure 10.—Comparison of predictions for turbomachinery benchmark problem, high frequency case. (a) Unsteady pressure distribution, real. (b) Unsteady pressure distribution, imaginary. (c) Upstream mean square pressure, x = –2. (d) Downstream mean square pressure, x = 3.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1997	Technical Memorandum

4. TITLE AND SUBTITLE

Fan Noise Prediction: Status and Needs

5. FUNDING NUMBERS

WU-538-03-11-00

6. AUTHOR(S)

Dennis L. Huff

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E-11022

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—97-206533
AIAA-98-0177

11. SUPPLEMENTARY NOTES

Prepared for the 36th Aerospace Sciences Meeting & Exhibit sponsored by the American Institute of Aeronautics and Astronautics, Reno, Nevada, January 12–15, 1998. Responsible person, Dennis L. Huff, organization code 2200, (216) 433-3913.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories: 07 and 71 Distribution: Nonstandard

This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

The prediction of fan noise is an important part to the prediction of overall turbofan engine noise. Advances in computers and better understanding of the flow physics have allowed researchers to compute sound generation from first principles and rely less on empirical correlations. While progress has been made, there are still many aspects of the problem that need to be explored. This paper presents some recent advances in fan noise prediction and suggests areas that still need further development. Fan noise predictions that support the recommendations are taken from existing publications.

14. SUBJECT TERMS

Aeroacoustics; Fan noise; Computational aeroacoustics

15. NUMBER OF PAGES	16. PRICE CODE
20	A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	